

## GUT Phase Transition and Hybrid Inflation

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### Abstract

The supersymmetric model of hybrid inflation is interesting not only because of its naturalness but also because of another reason. Its energy scale determined by the COBE normalization is  $10^{15}$ – $10^{16}$  GeV. It happens to be the energy scale of interest in particle physics, namely, the mass scale of right-handed neutrinos or the energy scale of the gauge-coupling unification. It is true that topological defects are produced after the hybrid inflation if it is related to a  $U(1)_{B-L}$  or a GUT-symmetry breaking, and hence one cannot naively identify models of particle physics with that of inflation. But those defects are not necessarily found in modified models. We show in this article that quite a simple extension of the minimal supersymmetric hybrid inflation model is free from monopoles or cosmic strings. Moreover, it happens to be exactly the same as a well-motivated extension of  $SU(5)$ -unified theories. The vacuum energy is dominated by F-term. The  $\eta$ -problem is not necessarily serious when the model is realized by D-branes. Although it has been considered that a coupling constant has to be very small when the vacuum energy is dominated by F-term, this constraint is not applied either to the D-brane model. They are due to a particular form of the Kähler potential and interaction of the model. Reheating process is also discussed.

Inflation explains naturally the initial conditions of the standard big-bang cosmology [1]. The universe had experienced superluminal expansion due to vacuum energy, before it underwent phase transition and entered into the radiation dominated Friedmann–Robertson–Walker universe. The original model [1] was associated with the first order phase transition of grand unified models of elementary particles. The idea was extremely attractive because the well-motivated model of particle physics was considered to provide a solution to serious problems in cosmology.

However, the inflation associated with the first order phase transition (referred to as the old inflation model) does not work [2, 3] because of its unsuccessful reheating process<sup>1</sup>. An alternative to the old inflation is the slow-roll inflation [5]. The positive vacuum energy lasts for sufficient amount of time not because the inflaton field is trapped at a local minimum of its potential, but because it rolls down the potential very slowly. The potential has to be extremely flat for this to happen. One of the important virtues of the slow-roll inflation is that it produces the scale-invariant density perturbation through the quantum fluctuation of the inflaton field.

It is far from natural, however, that there exists such a flat potential. Theorists have been working for decades to search for a natural model of inflation. The hybrid inflation model [6] is most promising among many trials. It has a natural and simple extension with supersymmetry (SUSY), and hence the flatness of the potential is preserved (to some extent) by radiative corrections. The minimal SUSY extension consists of three  $\mathcal{N} = 1$  SUSY chiral multiplets  $\Phi$ ,  $\Psi$  and  $\bar{\Psi}$ , and one U(1) vector multiplet  $V$ .  $\Psi$  and  $\bar{\Psi}$  are charged under the U(1) by  $\pm 1$ , while  $\Phi$  is neutral. The superpotential is [7, 8, 9]

$$W = \sqrt{2}\lambda\Phi(\Psi\bar{\Psi} - \zeta), \quad (1)$$

and there may be a Fayet–Iliopoulos D-term  $\mathcal{L} = -\xi D_V$ . The inflaton is  $\Phi$ . While its value is large,  $\Psi$  and  $\bar{\Psi}$  are at the origin, and the vacuum energy is  $\rho_{cos} = v_0^4 \equiv (1/2)(|\lambda(2\zeta)|^2 + g^2\zeta^2)$ , where  $g$  is the gauge coupling constant of the U(1) vector field. When the value of  $\Phi$  becomes sufficiently small,  $\Psi$  and  $\bar{\Psi}$  begins to be non-zero, and the slow-roll inflation comes to an end. The U(1) symmetry is broken down spontaneously, and the decay process of  $V, \Phi, \Psi$  and  $\bar{\Psi}$  reheats the universe. The potential of the inflaton  $\Phi$  is flat [7] even after supergravity corrections are taken into account (under certain assumptions, as we review later). Thus, this is a remarkably successful model.

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<sup>1</sup>A possible way out of this problem is proposed recently in [4].

Now, how is this model related to models of particle physics? The estimate of the energy scale  $\sqrt{\zeta}$  or  $\sqrt{\xi}$  is obtained by imposing the COBE normalization on the density perturbation,

$$\frac{\delta\rho}{\rho} = \frac{1}{\sqrt{75}\pi} \frac{V^{\frac{3}{2}}}{M_{\text{pl}}^3 V'} \simeq 1.9 \times 10^{-5}, \quad (2)$$

and assuming certain amount of e-fold number. It is roughly  $10^{15}\text{--}10^{16}$  GeV [10, 11]. It happens to be of theoretical interest from the point of view of particle physics. Namely, it is near the mass scale of right-handed neutrinos or the energy scale of unified theories. This coincidence has led many people to consider that the phase transition may be related to the symmetry breaking of  $U(1)_{B-L}$  or unified theories, where  $\Psi$  and  $\bar{\Psi}$  breaks those symmetries [8]. Difficulties in this direction are topological defects produced after the phase transition. If the phase transition is associated with the  $SU(5)_{\text{GUT}} \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$ , the GUT monopoles are created too much, in general. The above phase transition cannot be preceded by the inflation. This means that the simple  $SU(5)$  unification has to be abandoned, if the hybrid inflation were to be identified with the latest stage of the cascade break down of a large unified symmetry. If the minimal SUSY model is identified with the model of  $U(1)_{B-L}$ -symmetry breaking, the cosmic strings are created too much;  $\lambda \lesssim 10^{-4}$  is required [12, 13] to render the CMB distortion sufficiently small<sup>2</sup>.

The topological defects, however, are not inevitable predictions of unified theories or hybrid inflation. The topological defects associated with a symmetry breaking  $G \longrightarrow H$  are characterized by homotopy groups; cosmic strings by  $\pi_1(G/H)$  and monopoles by  $\pi_2(G/H)$ . They are determined by examining the homotopy exact sequence,

$$0 \rightarrow \pi_2(G/H) \rightarrow \pi_1(H) \rightarrow \pi_1(G) \rightarrow \pi_1(G/H) \rightarrow 0. \quad (3)$$

When  $G$  contains  $U(1)$ , as in the minimal SUSY model of hybrid inflation,  $\pi_1(G/H)$  tends to be non-trivial and the cosmic strings to be stable. When  $H$  contains  $U(1)$ , as in the standard model,  $\pi_2(G/H)$  tends to be non-trivial, and the monopoles tend to be in the spectrum. However, if both  $G$  and  $H$  contains  $U(1)$  and

$$(\pi_1(H) \simeq \mathbf{Z}) \rightarrow (\pi_1(G) \simeq \mathbf{Z}) \quad (4)$$

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<sup>2</sup>The constraint in the text is obtained in the case where the vacuum energy comes only from the D-term. It is loosened when the vacuum energy is dominated by F-term; this is because the tension of the cosmic string scales as  $(\lambda/g)\zeta$ , rather than  $\zeta$  or  $\xi$ . The constraint will be  $\lambda^2/g \lesssim 10^{-4}$ . Thus, the constraint is still stringent. *c.f.* [14], where the constraint in the F-term dominated case is discussed with an assumption  $\lambda = g$ .

is an isomorphism, just as in the electroweak phase transition ( $G \simeq \text{SU}(2)_L \times \text{U}(1)_Y \rightarrow (H \simeq \text{U}(1)_{QED})$ ), neither cosmic strings nor monopoles are left behind the phase transition.

The simplest extension along this line is to introduce an  $\text{SU}(2)$  vector multiplet and promote the chiral multiplets  $\Psi$  and  $\bar{\Psi}$  into “two Higgs doublets”;  $\Psi_i$  is  $(\mathbf{2}, +1)$  of  $\text{SU}(2) \times \text{U}(1)$ , and  $\bar{\Psi}^i$   $(\mathbf{2}, -1)$ . The superpotential is

$$W = \sqrt{2}\lambda\Phi(\Psi_i\bar{\Psi}^i - \zeta). \quad (5)$$

The parameter  $\sqrt{\zeta}$  is of the order of  $10^{15}$ – $10^{16}$  GeV. Since the values of  $\Psi_i$  and  $\bar{\Psi}^i$  are zero during the slow-roll stage, the extension does not affect the dynamics of inflation essentially<sup>3</sup>. When the slow-roll inflation comes to an end, the system falls down to the vacuum, and the symmetry is broken down to  $\text{U}(1)$ . It is remarkable that there is no vacuum moduli in this extension. All the particles in the spectrum have masses of the order of  $g\sqrt{\zeta}$  or  $\lambda\sqrt{\zeta}$  at the vacuum. Thus, this extension is free from moduli problem, and moreover, free from harmful relics of topological defects<sup>4</sup>. One can see that the same thing happens when the model is extended to  $\text{SU}(M) \times \text{U}(N)$  ( $M > N$ ) system with the superpotential

$$W = \sqrt{2}\lambda(\bar{\Psi}^i{}_\alpha\Phi\Psi^\alpha{}_i - \zeta\Phi) + \sqrt{2}\lambda'\bar{\Psi}^i{}_\alpha(t^a)^\alpha{}_\beta\Phi^a\Psi^\beta{}_i, \quad (6)$$

where  $\alpha, \beta = 1, \dots, N$  and  $i = 1, \dots, M$  denote  $\text{SU}(N)$  and  $\text{SU}(M)$  indices,  $t^a$  ( $a = 1, \dots, N^2 - 1$ ) are Hermitian matrices of the generators of the  $\text{SU}(N)$  Lie algebra, and  $\Phi^a$  are chiral multiplets. The gauge group is broken down to  $\text{SU}(N) \times \text{SU}(M - N) \times \text{U}(1)$  after phase transition. It is important to notice that the Fayet–Iliopoulos D-term parameter  $\xi$  has to vanish in this class of extensions, because there would be no supersymmetric vacuum otherwise. Thus, the vacuum energy is dominated by F-term.

Incidentally, there is a model of  $\text{SU}(5)$ -unified theories<sup>5</sup> that has exactly the same matter contents and superpotential as (6) [17]. The gauge group is<sup>6</sup>  $\text{SU}(5)_{\text{GUT}} \times \text{U}(3)_\text{H}$ , i.e.,  $M = 5$  and  $N = 3$ , at high energy, and is broken down to  $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$ , the standard-model gauge group. The parameter  $\sqrt{\zeta}$  provides the GUT scale,  $\sim 10^{16}$  GeV. This model

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<sup>3</sup>The coefficient of the 1-loop correction to the inflaton potential is changed.

<sup>4</sup>A model based on  $\text{SU}(2) \times \text{U}(1)$  gauge group is found in [8]. See also [15]. The relation between the defects and inflation is studied extensively in the context of grand unified theories in [16].

<sup>5</sup>We mean, by  $\text{SU}(5)$ -unified theories, those satisfying the following properties: a) there is a good explanation for the  $\text{SU}(5)$ -symmetric gauge-coupling unification, and b) the  $\text{U}(1)_Y$  charge assignment on quarks and leptons are explained in an elegant way in unified multiplets. The grand unification (combining all the forces into a single force) is not required; it is sufficient for both properties, but not necessary. Product groups are quite natural if models are embedded in brane world. Quantization of  $\text{U}(1)$  charges also follows naturally.

<sup>6</sup>There is a cousin model, whose gauge group is  $\text{SU}(5)_{\text{GUT}} \times \text{U}(2)_\text{H}$ . Review of this model can be found, e.g., in [18].

was obtained through discussion independent of cosmology and purely in the context of unified theories. It is one of a few classes of models that address the two major problems of unified theories in terms of symmetry; the problems are the doublet–triplet splitting and the suppressed dimension-five proton decay. For more details of this model, see [17] or review sections in [18, 19]. Thus, the phenomenologically well-motivated model of SU(5)-unified theories happens to have the same superpotential as the hybrid inflation model, and is free from the cosmic-string and monopole problems. The question is whether the model is able to realize the *slow-roll* inflation or not<sup>7</sup>.

Notice that the Fayet–Iliopoulos D-term parameter  $\xi$  has to be zero in the extended model, and hence the vacuum energy is dominated by F-term. Thus, there is so called  $\eta$ -problem [7, 10], as briefly explained below. If the vacuum energy were dominated by D-term, i.e.,  $\xi \neq 0, \zeta = 0$ , the inflaton potential would be [9]

$$V(\sigma) = \frac{1}{2}g^2\xi^2 \left( 1 + \frac{g^2}{4\pi^2} \ln \left( \frac{\sigma}{\sqrt{\xi}} \right) \right), \quad (7)$$

and is independent<sup>8</sup> of the Kähler potential (kinetic term) of  $\Phi$ . However, the potential becomes [7, 10]

$$V(\sigma) = \frac{1}{2}|\lambda 2\zeta|^2 \left( 1 + \frac{\lambda^2}{4\pi^2} \ln \left( \frac{\sigma}{\sqrt{\zeta}} \right) + \frac{k}{2} \left( \frac{\sigma}{M_{\text{pl}}} \right)^2 + \dots \right) \quad (8)$$

when  $\xi = 0, \zeta \neq 0$ , where

$$K = \Phi^\dagger \Phi - \frac{k}{4} \frac{(\Phi^\dagger \Phi)^2}{M_{\text{pl}}^2} + \dots \quad (9)$$

The slow-roll conditions are

$$\eta \equiv \frac{M_{\text{pl}}^2 V''}{V} \ll 1, \quad \epsilon \equiv \frac{1}{2} \left( \frac{M_{\text{pl}} V'}{V} \right)^2 \ll 1, \quad (10)$$

and they are sensitive to  $M_{\text{pl}}$ -suppressed corrections, such as the third term in (8). Thus, even the  $M_{\text{pl}}$ -suppressed corrections in the Kähler potential has to be under control ( $k \ll 1$ ) for the sufficiently flat potential. However, the second term in the Kähler potential seems to have the same symmetry property as the first term, and it is hard to understand why the second term in (9) is absent.

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<sup>7</sup>“Phase transition” in the title of this article may be a little misleading; strictly speaking, the phase transition is not the slow-roll stage, but a process of the graceful exit from inflation.

<sup>8</sup>It depends on the gauge kinetic term of  $V$ , instead. However,  $(\Phi/M_{\text{pl}})$ -corrections are absent there, if an  $R$  symmetry is imposed.

References [20] pointed out that the minimal SUSY hybrid inflation model with superpotential (1) can be compatible with an  $\mathcal{N} = 2$  SUSY<sup>9</sup>. An  $\mathcal{N} = 2$  rigid SUSY is enhanced in the U(1) gauge theory, i.e., in the inflation sector, when  $\lambda = g$ . It is considered in [20] that the enhanced SUSY may be responsible for solving the  $\eta$ -problem, since even the Kähler potential is under strict control of the SUSY.

If the hybrid inflation model with the superpotential (6) is identified with the model of unified theories, the  $SU(M = 5)_{\text{GUT}}$  gauge interaction connects the particles responsible for inflation/GUT-breaking with quarks and leptons. Thus, “the inflation/GUT-breaking sector” is not well-defined. Since the  $SU(5)_{\text{GUT}}$ -**adj.** chiral multiplet is not introduced in the model, and since quarks and leptons are in the chiral representations, there is no  $\mathcal{N} = 2$  SUSY in the total model. However, “the GUT-breaking sector” is decoupled (except through gravity) from other particles, when  $SU(5)_{\text{GUT}}$  interaction and a couple of others are turned off [21]. Thus, in this case, the corresponding statement is that the inflation/GUT-breaking sector is decoupled when some couplings are turned off, and the  $\mathcal{N} = 2$  rigid SUSY is enhanced in the decoupled sector when  $\lambda = g$  is satisfied [21]. Analyses of the model in [22, 18] suggests that the relation  $\lambda = g$  is preferred phenomenologically.

Although the inflation sector has the  $\mathcal{N} = 2$  rigid SUSY (if  $\lambda = g$ ), quarks and leptons have only an  $\mathcal{N} = 1$  SUSY. Thus, the gravity, which combines both of them, has only the  $\mathcal{N} = 1$  SUSY. In particular, the model of inflation has to be, in the end, embedded in an effective theory in  $D = 4$   $\mathcal{N} = 1$  supergravity. Thus, it is not easy to expect that the rigid  $\mathcal{N} = 2$  SUSY plays some roles in the flatness of the potential, since the slow-roll conditions (10) require  $M_{\text{pl}}$ -suppressed corrections be under control. Reference [20] considered that it may be in the following way that the  $\eta$ -problem is solved.

1. There should be a cut-off scale  $M_*$  other than  $M_{\text{pl}}$ , and  $M_* < M_{\text{pl}}$ . They are independent parameters, and there is a well-defined limit which takes  $M_{\text{pl}}$  to infinity, keeping  $M_*$  finite.
2. The inflation sector decouples completely from other sectors in that limit.
3. The  $\mathcal{N} = 2$  rigid SUSY is enhanced in that limit in the inflation sector.
4. Flat inflaton potential is obtained because the rigid  $\mathcal{N} = 2$  SUSY controls  $(\Phi/M_*)$ -corrections in the Kähler potential.
5. Finite  $1/M_{\text{pl}}$  effects provides the inflation sector only with the coupling of the particles in the sector with gravity. In other words, the effects do not alter the inflaton potential

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<sup>9</sup>The  $\mathcal{N} = 2$  SUSY was also discovered in [12].

directly.

Suppose that all these assumptions are correct. When the finite  $1/M_{\text{pl}}$  is restored from the limit, the only effect to the inflaton potential is through loop amplitudes. Loop factors and positive powers of  $(M_*/M_{\text{pl}})$  render the corrections small, and the potential flat.

If the inflation sector is identified with the GUT-breaking sector, some other interactions also have to be turned off in the limit in the assumption 1, and the assumption 5 has to hold true also for the finite effects of those couplings.

It was not clear in [20] what these assumptions imply, or whether they are justified or not. Moreover, there is an additional difficulty in cosmology in the presence of the  $\mathcal{N} = 2$  rigid SUSY; the spectrum in the inflation sector becomes degenerate if  $\lambda = g$ , and then the reheating does not proceed smoothly because of the degeneracy [20]. It was also unclear how this difficulty is solved. Embedding the model into Type IIB brane world clarifies the meaning of the assumptions, justifies some them, and solves the difficulty, as seen below.

The first progress in this direction was made in the context of unified theories [21]. The GUT-breaking sector and its interaction fit very well to the D3–D7 system of the Type IIB string theory. The  $D = 4$   $\mathcal{N} = 2$  SUSY  $SU(N) \times U(1)$  vector multiplets  $(V^a, \Phi^a)$  and  $(V, \Phi)$  come from D3–D3 open strings, and the hypermultiplet  $(\Psi^\alpha, \bar{\Psi}^i_\alpha)$  from the D3–D7 open strings. When the D3–D7 system is put into a Calabi–Yau 3-fold, the total theory has only  $D = 4$   $\mathcal{N} = 1$  SUSY. The low-energy effective theory should be given by  $D = 4$   $\mathcal{N} = 1$  supergravity. However, as long as the local geometry of a Calabi–Yau 3-fold around the D3-brane preserves the  $D = 4$   $\mathcal{N} = 2$  SUSY of the D3–D7 system, the matter contents and their interactions are rigid  $\mathcal{N} = 2$  supersymmetric (when quantum corrections are neglected) [21, 23, 19]. The  $D = 4$   $\mathcal{N} = 1$   $SU(M = 5)_{\text{GUT}}$  vector multiplet comes from D7–D7 open strings. The GUT phase transition is the process of D3–D7 bound state formation [23].

$N$  ordinary D3-branes were used for  $SU(N) \times U(1)$ , and the origin of the Fayet–Iliopoulos F-term parameter  $\zeta$  in (6) was identified with B-field background (although the zero mode is absent because of the orientifold projection) in [21].  $N$  fractional D3-branes on  $\mathbf{C}^2/\mathbf{Z}_M \times \mathbf{C}$  were used instead in [23], so that unwanted moduli (in Higgs branch) are removed. We thought that the vacuum expectation value (VEV) of twisted NS–NS sector fields may provide the non-vanishing Fayet–Iliopoulos parameter [23]. However, the  $U(1)$  vector field acquires masses as long as it is the centre-of-mass part of the  $N$  fractional D3-branes of the same type. Thus, another D-brane has to be introduced, and the  $U(1)$  will be identified with a linear combination<sup>10</sup> of the new  $U(1)$  and the centre-of-mass  $U(1)$  [19]. The D7-branes

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<sup>10</sup>The mode identified with the inflaton is not necessarily the same as the  $\mathcal{N} = 2$  SUSY partner of the

for  $SU(M = 5)_{\text{GUT}}$  are wrapped around a holomorphic 4-cycle, and chiral multiplets in the  $SU(5)_{\text{GUT}}\text{-adj.}$  representation are usually absent in the massless spectrum [21, 23, 19]. Reference [19] also discusses how to obtain Higgs particles, quarks and leptons from D-branes in curved Calabi–Yau 3-folds.

Note also that a model with fractional D3-branes and twisted NS–NS VEV was also proposed in [24] and one with ordinary D3-branes and B-field background in [25], both in the context of hybrid inflation. The relation between the inflation sector and the sector of quarks and leptons in realistic compactification was clearly described in [26].

The D-brane construction of the model gives us re-interpretation of the results obtained in field theories<sup>11</sup>. With the interpretation in terms of string theory, one can now proceed to address the  $\eta$ -problem, which could not be solved within the framework of  $D = 4$   $\mathcal{N} = 1$  supergravity. The assumption 1 is almost trivial, once we have a D-brane model. The Planck scale goes to infinity as the volume of a Calabi–Yau 3-fold becomes large, while the string scale remains finite. The assumption 2 is also justified, since all the modes except D3–D3 open strings are frozen in the large-volume limit. The inflation sector is now the D3–D7 system on  $\text{ALE} \times \mathbf{C}$  in this limit, and hence, it has a  $D = 4$  rigid  $\mathcal{N} = 2$  SUSY (assumption 3).

The rigid  $\mathcal{N} = 2$  SUSY helps in keeping the potential flat. The local geometry around the D3–D7 system has to be  $\text{ALE} \times \mathbf{C}$  so that the  $\mathcal{N} = 2$  SUSY is preserved. The translational invariance in the  $\mathbf{C}$  direction guarantees the flatness of the potential at the disc level. The effects of stringy-states exchange are at the cylinder level, and hence are suppressed by the string coupling constant. Moreover, they are well-organized so as not to give rise to exponentially growing potential of the inflaton [26]. Since it is mainly from heavy-state exchange amplitudes that higher-dimensional operators are expected to be induced, the most dangerous effects turn out to be harmless.

Although the above argument clearly shows the benefits of the  $\mathcal{N} = 2$  SUSY and string theory, yet it is not enough to justify the assumptions 4 and 5, or to guarantee that the potential is sufficiently flat. When the volume becomes finite, the closed-string modes become dynamical, and the inflation sector couples to various closed-string modes, not only to the  $D = 4$  gravity mode. The inflaton potential is generated when closed string moduli are integrated out [27] or when one takes account of the effects of twisted Ramond–Ramond field

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massless  $U(1)$  vector field.

<sup>11</sup>D-brane realization is not just a re-interpretation in the context of unified theories. It allows us to understand a couple of features of the model in a “unified” way. For more details, see [21] or review sections in [19].



exchange [26], and is not sufficiently flat, in general. Despite the generic difficulty, it is now clear that we have a framework in which gravitational and/or stringy corrections are under control and that one is able to see whether the potential is sufficiently flat or not. Various efforts have been made [28, 26, 29] in this direction, and have to be done further.

Let us now turn our attention to the possibility of identifying the GUT-breaking model with the model of hybrid inflation. The  $\eta$ -problem discussed so far is generic to all the cases when the vacuum energy is not dominated by D-term. Specific to the possibility is that the U(1) gauge-coupling constant is not small. Analysis in [11] shows that  $2g^2/(4\pi) \lesssim 10^{-3}$  is necessary for the sufficient e-fold number. This condition is not satisfied by the GUT-breaking model. The major cause of the stringent constraint is that the inflaton potential in the analysis begins to grow exponentially as the field value becomes of the order of  $M_{\text{pl}}$ ; the inflation should be realized by field value sufficiently smaller than  $M_{\text{pl}}$ . However, the potential does not grow exponentially in the D-brane model, even if the vacuum energy is dominated by F-term; this is because of a particular form of the Kähler potential and interaction [30, 26]. Therefore, the upper bound is not applied to the D-brane model, and hence, the GUT-breaking model is still eligible to be the model of hybrid inflation.

The large coupling constant implies large field value at the horizon exit. Naive analysis<sup>12</sup> using the potential (7) shows that the large coupling leads to large tensor/scalar ratio  $r \sim 10^{-2}$  ( $\epsilon \sim 10^{-3}$ ), and hence, there is a hope of detecting the tensor mode in the CMB polarization. However, using the potential (7) is too naive in deriving predictions, since the effects of closed-string exchange come in the same order as the 1-loop correction (as explicitly mentioned in [26]).

Finally, there is a remark on the difficulty in the reheating process. If the inflation sector has an exact rigid  $\mathcal{N} = 2$  SUSY, then the spectrum is completely degenerate, and it is difficult for all the particles to decay into lighter particles [20]. However, the degeneracy is lifted in the extended model based on  $SU(M) \times U(N)$  gauge group (e.g., [22, 18]); gauging  $SU(M)$  breaks the  $\mathcal{N} = 2$  SUSY. The mass eigenstates of massive  $SU(N) \times U(1)$  vector multiplets of  $D = 4$   $\mathcal{N} = 1$  SUSY are mixtures of those in  $U(N)$  and corresponding parts in  $SU(M)$ , and this mixing also enables the particles to decay [20]. Although the reheating process can be understood purely in terms of field theories, as above, yet it is remarkable that the gauging  $SU(M)$  is an immediate consequence in the D-brane model, rather than an additional assumption.

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<sup>12</sup>There should be no distinction between D-term and F-term in the local D-brane model. Thus, the  $D = 4$  effective action obtained by a simple Kaluza–Klein reduction should not have the difference. This is the reason why we consider the potential (7) to be a (very!) crude approximation.

If the hybrid inflation is realized by the GUT-breaking model [17], then one can see what happens in the reheating process. The spectrum analysed in [22, 18] tells us that the particles in the inflation sector can decay to lighter particles through renormalizable operators, and hence the reheating temperature is quite high. This allows the thermal leptogenesis [31] to take place, which will be followed by late-time entropy production [32, 33] so that the gravitino problem is avoided.

**Note** References [34, 35] appeared on the web just before we complete this article. They have a little overlap with this article.

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